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13. ABSTRACT ***(Maximum 200 Words)***

We are investigating new low-power confocal microwave technology to detect and image early-stage breast cancers. The new technology exploits the dielectric-property contrasts between normal breast tissues and malignant tumors and surrounding vascularization at microwave frequencies. The tumor-detection system employs a miniaturized, planar pulsed antenna array contacting only one side of the breast. The digital signal processing for the system is founded upon time-shifting and summing of the backscattered waveforms measured at each sensor element according to the assumption that a backscattering center is located at a particular trial point within the breast. The required time shift is the electromagnetic wave propagation delay between the trial point and the sensor element. To first-order accuracy, this delay depends upon the average dielectric properties of the local breast tissues. Patient-specific calibration of the microwave imager requires knowledge of these properties. To this end, this report summarizes the initial development of a two-dimensional inverse-scattering algorithm that permits a noninvasive measurement of the required dielectric properties of the first (skin) layer of the breast.

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Thesis advisor

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1 Introduction

We are investigating a new low-power pulsed confocal microwave technology to detect and image early-stage breast cancers. The new technology exploits the dielectric-property contrasts between normal breast tissues and malignant tumors and surrounding vascularization at microwave frequencies. The tumor-detection system employs a miniaturized, planar, pulsed antenna array contacting only one side of the breast. The digital signal processing for the system is founded upon time-shifting and summing of the backscattered waveforms measured at each sensor element according to the assumption that a backscattering center is located at a particular trial point within the breast. The required time shift is the electromagnetic wave propagation delay between the trial point and the sensor element. To first-order accuracy, this delay depends upon the average dielectric properties of the local breast tissues. Patient-specific calibration of the microwave imager requires knowledge of these properties. To this end, this report summarizes the initial development of a two-dimensional inverse-scattering algorithm that permits a noninvasive measurement of the required dielectric properties of the first (skin) layer of the breast. An initial guess for the dielectric parameters is provided to an FDTD element which calculates the reflected pulse at the surface. This pulse is subtracted from the measured response to yield a dirrerence (error) signal that is provided to a optimization routine. Based on the norm of the error signal, the routine generates an improved guess for the dielectric parameters. This improved guess is fed back to the FDTD element which calculates a new reflected pulse at the surface, and the process repeats until no further reduction of the error signal is possible. At this point, the final layer electrical properties used in the FDTD element can be taken to be the parameters of the physical system.

2 Body

In addition to inverse-scattering algorithm, I studied the anatomy and function of the female breast [1], [2], [3], [4]. Furthermore, I had personal communication with experts on properties of human tissues in microwave frequencies [5], [6], [7], in order to investigate possibilities for phantom materials to be used later in the program for the experimental verification.

The logic of our two-dimensional (2-D) finite-difference time-domain (FDTD) inverse-scattering algorithm is based on the work reported in the literature [8], [9]. We begin our investigations with simple 2-D geometry shown in Figure 1.

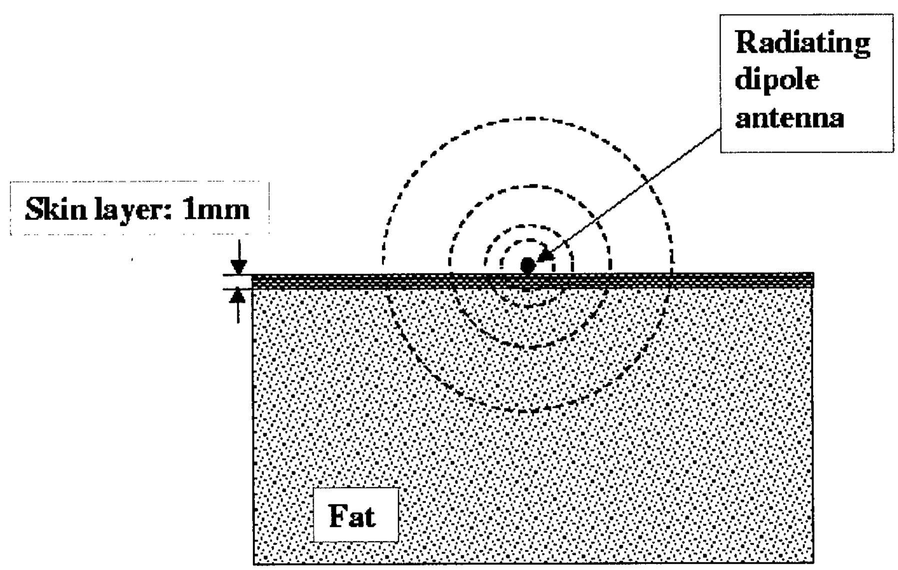

Figure 1: Geometry used in the 2-D FDTD model. The parameters of tissues at microwave frequencies are as follows: $\varepsilon_r(skin) = 36$, $\sigma(skin) = 4$ S/m, $\varepsilon_r(fat) = 18$, $\sigma(fat) = 0.4$ S/m.

A 120ps differentiated Gaussian pulse is emitted from the dipole antenna. This signal is subtracted from the backscattered responses of different cases under investigation. Figure 2 graphs three of these signals in time: the "reference" signal (the backscattered signal calculated based on the correct values of relative permittivity and conductivity of the skin layer) and two signals calculated when each of the parameters is perturbed individually. The graph illustrates that the relative perturbation of the relative skin permittivity has a greater effect on the backscattered signal than the same relative perturbation of the skin conductivity.

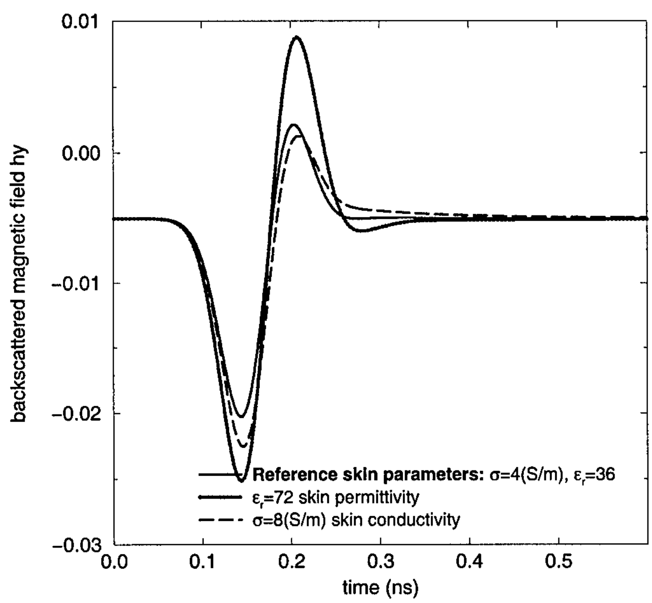

Figure 2: Backscattered signals for different values of $\varepsilon_r(skin)$ and $\sigma(skin)$.

First, we fix the value of $\sigma(skin)$ to its correct value, while making an initial guess for the $\varepsilon_r(skin)$. The FDTD code computes the backscattered signal for such $\varepsilon_r(skin)$, compares it to the reference signal (obtained with the correct value of $\varepsilon_r(skin)$ and calculates the error. Based on the error, $\varepsilon_r(skin)$ is decremented, and the FDTD computes the backscattered signal based on this new value of permittivity. The process is re-

peated, with varying decrement as needed, until the error is sufficiently small or when the calculated ε_r begins varying only within a narrow band of values. The results of two computations which follow the algorithm describe above is shown in Figure 3. Similar

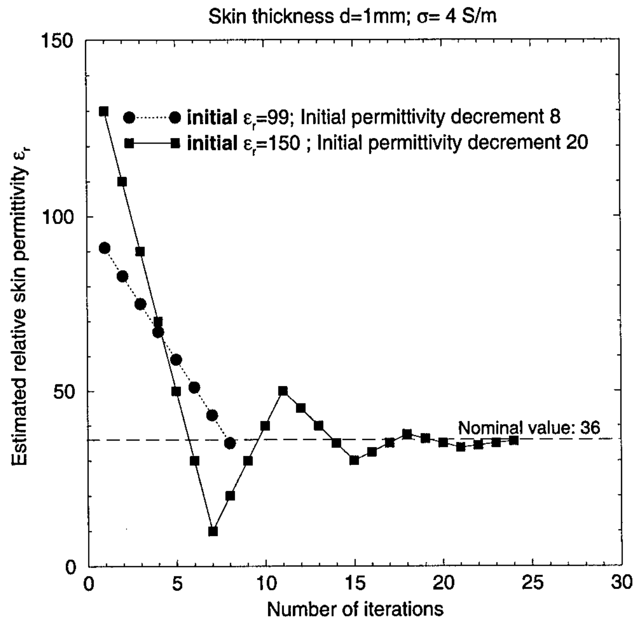

Figure 3: Convergence of $\varepsilon_r(skin)$ value for two different initial guesses.

procedure is followed for estimating the value of $\sigma(skin)$, while $\varepsilon_r(skin)$ is fixed to its correct value. The convergence of $\sigma(skin)$ is shown in Figure 4. Next, we must develop optimization scheme which would allow us to vary both electrical parameters of the skin. This is our current work. We apply the gradient vector method to follow a trajectory in the σ_r,- ε_r space as we converge to proper values of these parameters for the skin. The method is illustrated in Figure 5. From the initial guess GUESS#11, we make two more guesses, in the direction of x and y coordinate, respectively: GUESS#12 and GUESS#13. The errors form differences Δerror12 and Δerror12, which help us obtain the gradient vector to bring us to GUESS#21. The procedure is repeated as we follow the gradient trajectory to the final point of correct values of$\sigma_r(skin)$ and $\varepsilon_r(skin)$.

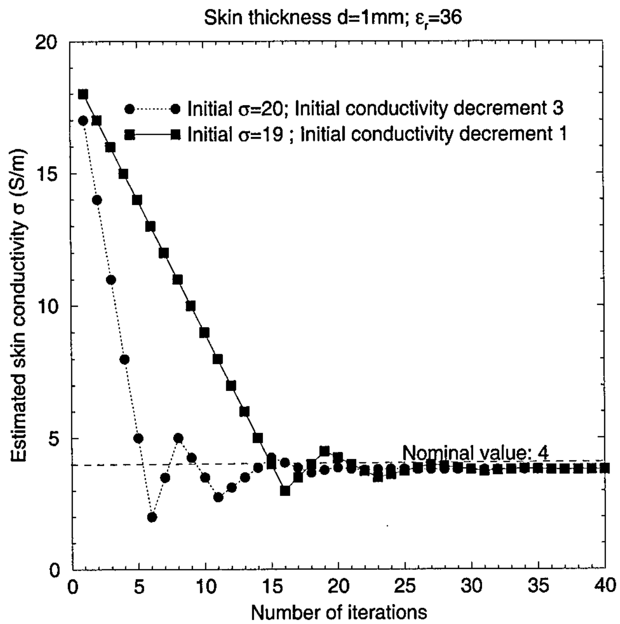

Figure 4: Convergence of $\sigma(skin)$ value for two different initial guesses.

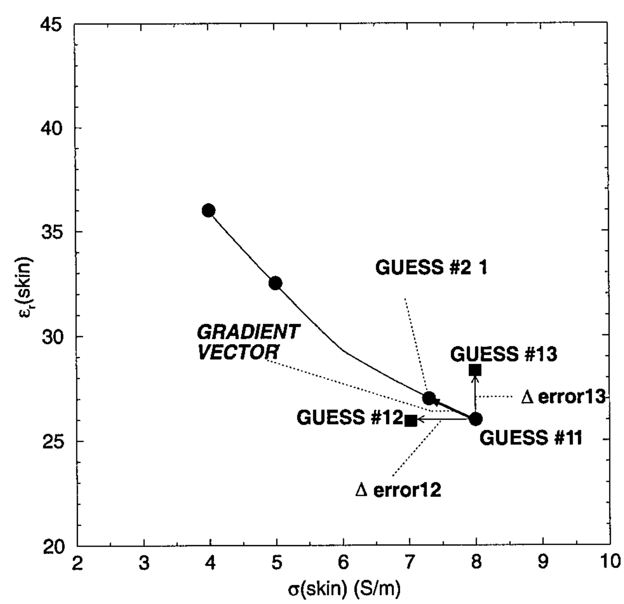

Figure 5: Trajectory of the gradient method leading to correct values of$\sigma_r(skin)$ and $\varepsilon_r(skin)$.

3 Key Research Accomplishments

- Study of anatomy and function of the female breast
- Development of 1-parameter inverse-scattering algorithm for the skin
- Current development of the 2-parameter gradient-based search method for the skin

4 Reportable Outcomes

- Pending patent application: "Microwave Discrimination Between Malignant and Benign Breast Tumors", US Patent Office Serial Number 90/120,749. Inventors: Jack E. Bridges, Susan Hagness, Alan Taflove and Milica Popovic.
- Best poster award, Electrical and Computer Engineering Department Research Fair, Northwestern University, May 1999.
- Bioelectromagnetics Society Annual Meeting, BEMS 2000, Munich, June 10-16, 2000. "Obtaining Microwave Properties of Near-Surface Body Tissues Using 2-D FDTD Inverse-Scattering Technique", M. Popovic and A. Taflove.
- Progress in Electromagnetics Research Symposium PIERS 2000, July 5-14, 2000, Cambridge, MA, USA. "Time Domain Inverse Scattering Technique for Obtaining Microwave Properties of Near-Surface Body Tissues", Milica Popovic and Allen Taflove.

5 Conclusions

As a principal investigator, I reported on my up-to-date results on the finite-difference time-domain inverse-scattering technique. Investigations have been done for 1-parameter case, and are currently being done for 2-parameter case for the skin layer, for the simplified geometry of the human female breast. The 2-parameter algorithm is based on the gradient method. An on-going effort is invested in studying function and anatomy of female breast. Furthermore, additional research is done to find materials that would serve for the phantom of the breast anatomy at microwave frequencies. Note: in the statement of work of my proposal, it is stated that Specific Aim 3 is to be conducted using laboratory facilities of Interstitial, Inc. Due to moving of these facilities to another location, experimental work is planned to be done at the laboratory facilities available at Northwestern University in the Electrical and Computer Engineering Department. The information reported in the body of this report has not yet been published and should therefore be protected.

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PHANTOM MODEL AND 3-D FEM SIMULATIONS: CONDUCTION OF EXTERNALLY GENERATED LOW-FREQUENCY SIGNALS THROUGH MUSCLES. M. Popovic [1], A. Taflove [1*], N. Stoykov [2*] and T.A. Kuiken [2*], [1] Northwestern University, Evanston, Illinois 60208, USA. [2] Rehabilitation Institute of Chicago, Chicago, Illinois 60611, USA.

OBJECTIVE: Our present research is aimed at developing a better understanding of conduction and propagation of signals through the muscles of the human arm. Such an improved understanding may permit improved operation of controlled prosthetic arms for above- and below-elbow amputees. We have conducted initial numerical and experimental investigations of muscle as a passive load when connected to external sources. To confirm our experimental methods and verify the numerical model, we have used a phantom model of muscle tissue as a subject. METHOD: We constructed an experimental model of the muscle tissue using a cylindrical phantom made of commercially available ground meat. Pairs of electrodes were placed symmetrically around the phantom. One pair was connected to the external source (CW at 30 Hz, 70 Hz, 120 Hz, 400 Hz and 4 kHz), while the other pairs were used as recording electrodes for quantifying signal conduction through the phantom. Using a gain-phase meter, the permittivity and conductivity of the material used in the phantom was measured over the range 30 Hz – 4 kHz. In parallel with our experimental phantom studies, we developed a numerical model of the muscle phantom, we used the commercially available FEM software tool EMAS™ by Ansoft. The FEM model included the measured electrical parameters for the phantom tissue. At specific locations within the FEM model, a current source was specified to simulate the external source used in the experiments. The potential distribution was calculated and values of the potential observed at locations corresponding to those of the recording electrode sites. This enabled direct comparison with the measurements. RESULTS: We have found a significant effect of tissue permittivity and displacement currents for signal propagation in the frequency range 30Hz – 4kHz. DISCUSSION: Previous models of low-frequency signal propagation in muscles largely ignored the effects of tissue permittivity and displacement currents. New models incorporating such effects have the potential to study the possibility of minimizing crosstalk between individual electrode sites, also investigating more complex geometries which can include insulating materials within the phantom. This analysis could aid in development of refined control of the externally powered myoelectrically controlled prosthetic device. This research was generously sponsored by the Whitaker Foundation.

Time Domain Inverse Scattering Technique for Obtaining Microwave Properties of Near-Surface Body Tissues

Milica Popovic and Allen Taflove

This paper reports a time-domain inverse-scattering algorithm that permits a noninvasive measurement of microwave properties of the near-surface body tissues. We use the measured "early-time" response of an ultrawide-band sensor element to unfold the dielectric properties and thickness of the skin and the average dielectric properties of the tissue beneath the skin. The measured data are time samples of $Z(t)$, the ratio of the voltage and current waveforms observed at the driving point of each element.

We analyze the $Z(t)$ data by adapting the technique reported in [1] for unfolding the properties of a layered half-space from plane-wave pulse-reflection measurements taken at its surface. Here, an initial guess for the layer thicknesses and dielectric parameters is provided to an FDTD forward-scattering code which calculates the reflected pulse at the surface. This pulse is subtracted from the measured response to yield an error signal that is provided to a Levenberg-Marquardt (LM) nonlinear optimization routine. Based upon the norm of the error signal, the LM routine generates an improved guess for the layer thicknesses and dielectric parameters. This improved guess is fed back to the FDTD element which calculates a new reflected pulse at the surface and the process repeats. Convergence occurs when no further reduction of the error signal is possible. At this point, the final layer thicknesses and electrical properties used in the FDTD element are taken to be parameters of the physical system.

In the present problem, the excitation is not a normally incident plane wave. Instead, it is an approximately spherical wave originating at the feedpoint of the antenna element. The method of [1] must therefore be adapted. In this initial work, we implement this change by substituting a 2-D forward-scattering FDTD code for the 1-D forward-scattering FDTD code reported in [1]. Representative numerical simulations are provided that include the effects of simulated additive Gaussian noise.

The proposed technique may assist the development of recently reported noninvasive microwave imaging schemes utilizing the backscatter of short pulses. Such methods require a good estimate of the average skin thickness and properties of the underlying tissues to unfold the impulsive backscattered waveform, thereby obtaining an image of subcutaneous tissues.

Reference

[1] K. R. Umashankar *et al.*, *J. Electromagn. Waves Apps.*, vol. 8, pp. 489-509, 1994.

Topic category: ***1. Electromagnetic theory, diffraction, scattering and inverse scattering***

Preferred presentation: ***platform***